

Nucleotide Sequence of the *iucD* Gene of the pColV-K30 Aerobactin Operon and Topology of Its Product Studied with *phoA* and *lacZ* Gene Fusions

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Gene *iucD* of the aerobactin operon of the *Escherichia coli* plasmid ColV-K30 encodes a membrane-bound enzyme synthesizing N^{α} -hydroxylysine, the first product of the aerobactin biosynthesis pathway. The entire nucleotide sequence of the cloned *iucD* gene was determined, from which the primary and some aspects of the secondary structure of the encoded peptide were deduced. *E. coli* cells harboring multicopy plasmid pVNL12 (*iucD*⁺) hyperproduced an approximately 50-kilodalton peptide which was purified and identified as the product of the gene by examination of its amino-terminal sequence. Two *iucD*'-'*lacZ* gene fusions were constructed *in vitro* and four *iucD*'-'*phoA* gene fusions were generated *in vivo* by mutagenesis of *iucD* with transposon TnphoA (Tn5 IS50_L::*phoA*). Analysis of the corresponding fusion proteins suggested at least two domains of attachment of the IucD protein to the inner side of the cytoplasmic membrane. The first apparent membrane-bound domain was found within the first 25 amino acids of the protein and showed a sequence which resembled that of the signal peptides.

Under conditions of iron stress, most bacteria induce high-affinity iron transport systems mediated by the chelators named siderophores (9, 42). The most thoroughly studied system is that encoded by the *Escherichia coli* virulence plasmid ColV-K30, which uses the siderophore aerobactin as an iron scavenger. This system is arranged in a single operon (11, 16, 24) driven by an iron-dependent promoter (6), which makes it an ideal model for study of the organization and transcriptional regulation of metal-sensing genes. Furthermore, the aerobactin system seems to be an important virulence determinant in nosocomial infections (for a review, see reference 14) and hence constitutes a potential target for new antimicrobial drugs.

The entire aerobactin system spans about 8 kilobases (kb) of pColV-K30, including a cluster of five genes transcribed coordinately through a strong promoter (6) located at the front of the first gene (Fig. 1). Transcription of the operon is controlled, as in other iron-regulated systems in *E. coli*, by the product of the *fur* gene (2, 26), a repressor protein which uses Fe(II) as corepressor to bind to an operator region in the aerobactin promoter (4, 17). Four of the five genes (*iucA* to *iucD*) are involved in the biosynthesis of the siderophore, while the remaining gene (*iutA*) determines an outer membrane receptor for the ferri-aerobactin complex. The function of each gene in subsequent steps of siderophore synthesis is known (16, 24), and their peptide products have been identified. In two cases (*iucB* and *iutA*), the proteins have been purified and their activity has been assessed *in vitro* (13, 34).

The product of the gene *iucD* is of special interest for two reasons. First, it catalyzes a unique type of enzymatic reaction which does not occur in animal tissues, namely, the N^{α} -oxygenation of lysine. Second, *iucD* mediates the first step of aerobactin biosynthesis, and hence effective inhibitors of its activity may have therapeutic value.

A previous study (32) had shown the product of gene *iucD* to be bound to the cytoplasmic membrane, although the

function of the protein was uncertain at that time. In the present work we have determined the complete nucleotide sequence of the *iucD* gene and purified the corresponding peptide product. Structural features of the protein and details of its association to the inner membrane of *E. coli* were suggested by the analysis of *iucD*'-'*phoA* and *iucD*'-'*lacZ* gene fusions.

MATERIALS AND METHODS

Culture media, strains, and plasmids. Unless otherwise indicated, all cultures were grown at 37°C in LB medium (41) to which adequate levels of antibiotics (either ampicillin or ampicillin plus kanamycin) were added to ensure retention of the plasmids. Strains used are listed in Table 1. *E. coli* 71-18 was used as the host of all recombinant M13 clones for sequencing. *E. coli* LE392 was used for lytic growth of λ TnphoA (Tn5 IS50_L::*phoA*), and *E. coli* CC118 was used as the recipient for TnphoA mutagenesis of *iucD* (see below). Plasmid pVNL12 (Fig. 1) contains an approximately 3.1-kb *Bam*H-I-EcoRI DNA fragment from the aerobactin operon (16) cloned at the corresponding sites of the pUC9 vector (52). This plasmid contains the complete sequence of *iucD* plus partial sequences of the flanking genes in the operon (17), *iucC*, and *iutA* (Fig. 1). The *iucD* gene in pVNL12 is expressed through the strong *lac* promoter of pUC9 (54). Plasmids resulting from the construction of *phoA* and *lacZ* gene fusions (see Table 2) will be described in the Results section.

DNA manipulation, enzymatic assays, and chemical determinations. All DNA techniques, including plasmid construction, ligation, preparation of competent *E. coli* cells, transformation, and fragment purification, were carried out by standard procedures (37) or following the directions of commercial suppliers. Restriction endonucleases were purchased from New England Biolabs, Inc., and "slow" *Bal*31 nuclease (1 U/μl) was from International Biotechnologies, Inc. β-Galactosidase activity was measured by the method of Miller (41), and alkaline phosphatase activity was determined as previously described (40). The IucD⁺ phenotype

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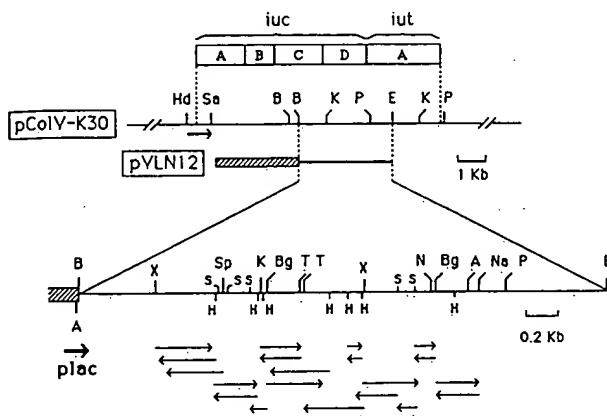


FIG. 1. Strategy for sequencing the *iucD* gene. Top: Genetic organization of the aerobactin operon lined up with a partial restriction map of the corresponding DNA segment of pColV-K30. The native iron-regulated promoter of the system (6) is located in front of *iucA* and is indicated by an arrow. Bottom: Enlarged representation of the portion of the aerobactin cluster cloned in pVLN12 which contains the *iucD* gene. The orientation of the *lac* promoter from vector pUC9 (through which the *iucD* gene is transcribed in pVLN12) is indicated, as are the restriction sites used to generate M13 clones for sequencing. Thin arrows indicate the location and orientation of the inserts in those M13 clones. Abbreviations: A, *Acc*I; B, *Bam*HI; Sp, *Sph*I; E, *Eco*RI; Hd, *Hind*III; H, *Hpa*II; K, *Kpn*I; N, *Nco*I; Na, *Nar*I; P, *Pvu*II; S, *Sau*3A1; Sa, *Sal*I; Sp, *Sph*I; T, *Taq*I; X, *Xba*I.

was tested by assaying for hydroxylamine in the culture supernatants of the corresponding strains with the Csaky test, as modified by Gillam et al. (21).

Sequencing strategy and sequence analysis. The approximately 2.3-kb DNA fragment generated by treating pVLN12 with the restriction endonuclease *Acc*I, which overlaps most of the insert in pVLN12 (Fig. 1), was purified and digested separately with the enzymes *Sau*3A1 and *Hpa*II. The resulting fragments were repurified from polyacrylamide gels (37) and cloned at compatible sites of the replicative forms of M13mp18 and M13mp19 phages. The inserts of single-stranded forms of the resulting constructions were sequenced by the dideoxynucleotide method (46). To confirm and complete the sequence of both DNA strands of the 2.3-kb *Acc*I segment, *Xba*I, *Sph*I, *Kpn*I, *Taq*I, *Bgl*II, and *Nar*I restriction endonucleases were used to generate additional fragments which were isolated, cloned, and sequenced by the same procedure (Fig. 1). The nucleotide sequence obtained was analyzed with a Sequence Analysis program from the Department of Biochemistry and Biophysics of the University of California at San Francisco and with a Mac Gene program from Applied Genetic Technology (Fairview Park, Ohio).

Protein techniques. Proteins hyperexpressed by *E. coli* strains carrying recombinant plasmids were isolated directly from whole-cell lysates of the corresponding strains as follows. After overnight growth in LB medium (41) with appropriate antibiotics, cells were spun down, suspended in sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) sample buffer (36), boiled for 3 min, and loaded in 8 to 10% polyacrylamide gels (36). The position of the protein bands of interest with respect to the migration of prestained molecular weight standards (Sigma Chemical Co.) was known in advance, and the corresponding slice of the unfixed gel was cut out and electroeluted in 80 mM TBE

buffer pH 8.3 (37) with an electroseparation device (Elutrap; Schleicher & Schuell) (30). The peptidic material recovered was precipitated in 10% trichloroacetic acid, washed in ethanol, and lyophilized. Analysis of the amino-terminal sequence of electroeluted protein bands was carried out in the Department of Biochemistry and Biophysics of the University of California at San Francisco.

Periplasmic proteins were released from *E. coli* cells by the chloroform shock procedure (18), dissolved in SDS-PAGE sample buffer (36), and analyzed in polyacrylamide gels as described above.

Spheroplasts from cells carrying gene fusion plasmids were prepared and analyzed as follows. Overnight cultures of the *E. coli* strains harboring the different plasmids were spun down and suspended in the same volume of a solution containing 2 mM EDTA, 0.58 M sucrose, and 30 mM Tris hydrochloride (pH 8). Lysozyme was then added to 100 µg/ml. Conversion of cells into spheroplasts was monitored with a light microscope. Spheroplasts were spun down, suspended in an equal volume of the same buffer without lysozyme, and split into two parts, one of them being treated with trypsin (0.6 µg/ml) (Sigma, T8642) for 30 min at 22°C. Treated and untreated spheroplasts were then spun down, suspended directly in SDS-PAGE sample buffer, boiled for 3 min, and analyzed in an SDS-PAGE system (36) as described above.

Construction of gene fusions. Alkaline phosphatase gene fusions to *iucD* were obtained in vivo by infecting *E. coli* CC118 harboring pVLN12 (*iucD*⁺) with λ *TnphoA* as described (25). After infection, cells were plated on LB agar with kanamycin (300 µg/ml) and 40 µg of the chromogenic substrate 5-bromo-4-chloro-3-indolyl phosphate (XP; Sigma) per ml. High-kanamycin-concentration-resistant colonies were examined for the PhoA⁺ phenotype (blue in plates with XP) and for the production of hydroxylamine. Insertions of *TnphoA* into pVLN12 were mapped by restriction enzyme analysis of the corresponding plasmids. When necessary, the precise boundaries of the *iucD*'-*phoA* sequence junction were determined by sequencing, in an M13 system (see above), restriction fragments overlapping the junctions.

TABLE 1. Characteristics of relevant *E. coli* strains, phages and plasmids

| Strain, phage, or plasmid | Genotype or description | Source or reference |
|---------------------------|--|---------------------|
| <i>E. coli</i> | | |
| 71-18 | Δ(<i>lac proAB</i>) <i>thi supE F' proAB lacI^QZΔM15</i> | R. Kolter |
| CC118 | F ⁻ Δ(<i>ara-leu</i>)7697 <i>araD139 ΔlacX74 galE galK phoA20 thi rpsE rpoB argE(Am)recA1</i> | C. Manoil |
| LE392 | F ⁻ <i>supF supE hsdR galK trpR metB lacY tonA</i> | C. Manoil |
| λ <i>TnphoA</i> | <i>b221 cI857 Pam3</i> with <i>TnphoA</i> in or near <i>rex</i> | C. Manoil |
| Plasmids | | |
| pMLB1034 | Ap ^r <i>lacZ</i> gene fusion vector | 48 |
| pVLN12 | Ap ^r <i>iucD</i> ⁺ | 16 |
| pOV7 | Ap ^r <i>iucD</i> '- <i>lacZ</i> | This study |
| pOV9 | Ap ^r <i>iucD</i> '- <i>lacZ</i> | This study |
| pOV5 | Ap ^r Km ^r <i>iutA</i> ':: <i>TnphoA</i> | This study |
| pOV25 | Ap ^r Km ^r <i>iutA</i> ':: <i>TnphoA</i> | This study |
| pOV33 | Ap ^r Km ^r <i>iucD</i> ':: <i>TnphoA</i> | This study |
| pOV99 | Ap ^r Km ^r <i>iucD</i> ':: <i>TnphoA</i> | This study |
| pOV48 | Ap ^r Km ^r <i>iucD</i> ':: <i>TnphoA</i> | This study |
| pOV28 | Ap ^r Km ^r <i>iucD</i> ':: <i>TnphoA</i> | This study |

Two β -galactosidase gene fusions were obtained in vitro by ligating the 3.3-kb *Sma*I-*Bam*I fragment of pMLB1034 vector (48), containing a *lacZ* gene devoid of promoter and of ribosome-binding sequence, into plasmid pVNL12 digested with either *Kpn*I or *Nco*I and treated for a short time with *Bal* 31 enzyme. This last treatment was made to ensure the presence of all possible reading frames. The ligation mixtures were used to transform *E. coli* CC118. Transformant blue colonies arising in LB with 150 μ g of ampicillin and 40 μ g of 5-bromo-4-chloro-3-indolyl- β -D-galactoside (Sigma) solid medium per ml were picked for further analysis (see Results section).

RESULTS

Sequence of the *iucD* gene. pVNL12 (16) carries the active *iucD* gene in a 3.1-kb insert from pColV-K30 in pUC9. As the sequence of the following gene (*iutA*) is known (34) as well as the transcriptional orientation (6), we focused our attention on a 2.3-kb *Acc*I restriction fragment of pVNL12 in which the *iucD* gene sequence was expected to map. Figure 1 shows the collection of inserts in M13 clones which were used for sequencing the entire region. Each nucleotide was sequenced an average of three times.

Only one open reading frame of sufficient length to encode the IucD protein, previously sized in minicell systems in the range of 50 kilodaltons (kDa) (11, 16, 24, 32, 33), could be found with the transcriptional orientation of the aerobactin operon. The sequence of that open reading frame is shown in Fig. 2. This structural sequence (1,278 base pairs [bp]) contained an ATG start codon located 9 bp downstream from an AGGA sequence which might form part of a ribosome-binding site (47). The putative structural region spanned 426 amino acid residues and ended with the stop codon TAG. Of the residues, 48% were hydrophobic, 26% were polar uncharged, 15% were positively charged, and 11% were negatively charged. The predicted molecular weight of this peptide was 48,968. Figure 3 shows the hydrophobicity of the protein throughout the entire sequence according to Kyte and Doolittle (35).

The sequences upstream and downstream of the *iucD* structural gene were also examined. Most of the approximately 850 bp between the *Bam*HI site and the start of the *iucD* gene overlapped the structural sequence of the preceding gene in the operon, *iucC*, although the precise boundaries are unknown. No evident promotorlike sequences, i.e., -35 and -10 consensus sequences, were detected either upstream or downstream of *iucD*. Interestingly, the intercistronic regions at both sides of *iucD* contained short regions of dyad symmetry (Fig. 2). The dyad preceding the *iucD* structural gene would allow the formation of a stem-loop structure in the corresponding transcript with a calculated ΔG value of -20.6 kcal/mol, while the dyad succeeding the gene would have a ΔG of -17.6 kcal/mol.

Isolation and identification of the *iucD* protein product. *E. coli* cells harboring pVNL12 hyperproduced an approximately 50-kDa peptide when analyzed in SDS-PAGE systems (not shown). This polypeptide had a molecular weight similar to that of a protein identified in minicells as the product of the *iucD* gene (16, 24). To ascertain whether this peptide was indeed the product of the gene and to check the reading frame obtained from nucleotide sequence data, we purified this protein band and subjected it to amino-terminal analysis. *E. coli* CC118 harboring the plasmid pOV25 was used as the source of the protein (see below). For unknown reasons, this plasmid construction afforded further hyperex-

pression of the approximately 50-kDa protein to a level close to 5% of the total cell protein (see Fig. 5). The protein band was purified from a whole-cell extract by electroelution from a polyacrylamide gel. The initial 15 amino acids of the isolated polypeptide were identified as NH₂-Met-Lys-Lys-Ser-Val-Asp-Phe-Ile-Gly-Val-Gly-Thr-Gly-Pro-Phe. These are the same residues expected from the translated sequence, including the initial methionine as the amino terminus. This result allowed the unequivocal assignment of the approximately 50-kDa protein as the product of the *iucD* gene.

***phoA* and *lacZ* gene fusions to *iucD*.** Alkaline phosphatase in *E. coli* must be exported into the periplasm to be active (28, 40). Therefore, *phoA* gene fusions are a convenient method to probe the topology of putative membrane-bound and exported proteins (7, 38, 39). To construct a number of *iucD*'-*phoA* gene fusions, we mutagenized an *E. coli* strain harboring the plasmid pVNL12 with Tn_{phoA} and selected insertions of the transposon in the multicopy plasmid with a high concentration of kanamycin. Should the product of *iucD* be a membrane-associated protein and should it have domains facing the periplasm, colonies with a PhoA⁺ phenotype concomitant with the loss of hydroxylamine production (*iucD*) should be isolated after mutagenesis. A number of blue colonies in XP medium indeed appeared after Tn_{phoA} mutagenesis, and they were picked for further analysis. Most of the deep-blue colonies resulted from insertions in the sequence of *iutA* present in pVNL12. This was expected since the truncated sequence of *iutA* remaining in pVNL12 (Fig. 4) keeps the intact signal peptide sequence necessary for protein export (34). The appearance of these conspicuous PhoA⁺ colonies due to insertions in *iutA* constituted an internal control for the performance of the procedure.

Figure 4 summarizes the location and orientation of the Tn_{phoA} insertions found. Four insertion derivative plasmids, pOV33, pOV99, pOV48, and pOV28, conferred a PhoA⁺ IucD⁻ phenotype and were studied in more detail. As a complement to the *phoA* fusions, we also obtained two *iucD*'-*lacZ* gene fusions in vitro as described in the Materials and Methods section, which were termed pOV7 and pOV9. The precise positions of fusion junctions were confirmed by nucleotide sequencing, and they are indicated in Fig. 3 and Table 2.

Analysis of IucD'-PhoA and Iuc'-LacZ fusion proteins. The levels of alkaline phosphatase and β -galactosidase afforded by *E. coli* cells carrying different *phoA* and *lacZ* fusions are shown in Table 2. All four *iucD*'-*phoA* fusions (carried in pOV33, pOV99, pOV48, and pOV28) afforded phosphatase activity, although the levels varied significantly in each fusion. Cells harboring pOV33 and pOV99 showed 15- to 20-fold-higher levels of phosphatase than those with pOV48 and pOV28, while an *iutA*'-*phoA* fusion used as a positive control of effective export (pOV5) had levels five-fold above those of the most active *iucD*'-*phoA* fusion (pOV33).

Plasmids with *iucD*'-*lacZ* fusions (pOV7 and pOV9) afforded rather high values for β -galactosidase activity (Table 2). Permeabilization of cells prior to the assay resulted in a 16-fold increase in β -galactosidase activity detected in cells carrying pOV7, while the same treatment produced an increase of only 2.5-fold in those with pOV9.

Figure 5 shows the protein profile of *E. coli* cells harboring the plasmids with the *iucD*'-*phoA* and *iucD*'-*lacZ* fusions analyzed in an SDS-PAGE system. In all cases, hyperproduction of a protein of the approximate size of the predicted

SphI

S.D.

CCGGTAAACTGACCTGGCCTGATCTGGATGGCGACCGCATCGCTGCCATTACCTTGAGGATCTGCAAAATCCGCTGTGGCTGCTAACTCAGGAATATGAATC

| | | | |
|---|----|---|---|
| 1 | 10 | | 20 |
| | | Met Lys Lys Ser Val Asp Phe Ile Gly Val Gly Pro Phe Asn Leu Ser Ile Ala Ala Leu Ser His Gln Ile Glu Glu Leu Asp | |
| | | ATG AAA AAA AGT GTC GAT TTT ATT GGT GTA GGG ACA GGG CCA TTT AAT CTC ACC ATT CCT CGG TTG TCA CAT CAG ATC GAA GAA CTG GAC | |
| | | 40 | 50 |
| | | Cys Leu Phe Phe Asp Glu His Pro His Phe Ser Trp His Pro Gly Met Leu Val Pro Asp Cys His Met Gln Thr Val Phe Leu Lys Asp | |
| | | TGT CTC TTC TTT GAT GAA CAT CCT CAT TTT TCC TGG CAT CGG CGT ATG CTG GTA CGG GAT TGT CAT ATG CAG ACC GTC TTT CTG AAA GAT | |
| | | 70 | 80 |
| | | Leu Val Ser Ala Val Ala Pro Thr Asn Pro Tyr Ser Phe Val Asn Tyr Leu Val Lys His Lys Lys Phe Tyr Arg Phe Leu Thr Ser Arg | |
| | | CTG GTC AGT GCT GTT GCA CCT ACA AAT CCC TAC AGT TTT GTT AAC TAT CTG GTG AAG CAC AAA AAG TTC TAT CGG TTC CTT ACA AGC AGA | |
| | | 100 | 110 |
| | | Leu Arg Thr Val Ser Arg Glu Glu Phe Ser Asp Tyr Leu Arg Trp Ala Ala Glu Asp Met Asn Asn Leu Tyr Phe Ser His Thr Val Glu | |
| | | CTA CGT ACA GTC TCC CGT GAA GAG TTT TCT GAC TAC CTC CGC TGG GCT GAA GAT ATG AAT AAC CTG TAT TTC ACT CAT ACC CTT GAA | |
| | | 130 | 140 |
| | | Asn Ile Asp Phe Asp Lys Lys Arg Arg Leu Phe Leu Val Gln Thr Ser Gln Gly Gln Tyr Phe Ala Arg Asn Ile Cys Leu Gly Thr Gly | |
| | | AAC ATT GAT TTC GAT AAA AAA CGT CGA TTG TTT CTG GTG CAA ACC AGC CAG GGA CAA TAT TTT GCC CGC AAT ATC TGC CTT GGT ACA GGA | |
| | | 160 | 170 |
| | | Lys Gln Pro Tyr Leu Pro Pro Cys Val Lys His Met Thr Gln Ser Cys Phe His Ala Ser Glu Ser Asn Leu Arg Arg Pro Asp Leu Ser | |
| | | AAA CAA CCT TAT TTA CCA CCC TGT GTG AAG CAT ATG ACA CAA TCC TGT TTC CAT GCC ACT GAA AGT AAT CTT CGT CGG CCG GAT CTT ACT | |
| | | 190 | 200 |
| | | Gly Lys Arg Ile Thr Val Val Gly Gly Gln Ser Gly Ala Asp Leu Phe Leu Asn Ala Leu Arg Gly Glu Trp Gly Glu Ala Ala Glu | |
| | | GGA AAA CGG ATA ACC GTG GTT GGT GGA GGA CAG AGT GGT GCA GAC CTG TTC AAT GCA TTA CCC GGG GAA TGG GGA GAA CGG GCG GAA | |
| | | 220 | 230 |
| | | Ile Asn Trp Val Ser Arg Arg Asn Asn Phe Asn Ala Leu Asp Glu Ala Ala Phe Ala Asp Asp Tyr Phe Thr Pro Glu Tyr Ile Ser Gly | |
| | | ATA AAC TGG GTG TCC CGG CCT AAT AAT TTT AAC GCA CTC GAT GAG CCT GCT TTT GCT GAT GAT TAT TTT ACA CCT GAA TAT ATT TCA GGC | |
| | | 250 | 260 |
| | | Phe Ser Gly Leu Glu Glu Asp Ile Arg His Gln Leu Leu Asp Glu Gln Lys Thr Asp Ile Gly Trp His His Cys Pro Ile Leu Leu | |
| | | TTC TCC GGA CTG GAG GAA GAT ATT CGC CAT CAG TTA CTG GAT GAG CAG AAA ACT GAC ATC GGA TGG CAT CAC TGC CGG ATT CTT TTA CTG | |
| | | 280 | 290 |
| | | Thr Ile Tyr Arg Glu Leu Tyr His Arg Phe Glu Val Leu Arg Lys Pro Arg Asn Ile Arg Leu Leu Pro Ser Arg Ser Val Thr Thr Leu | |
| | | ACC ATT TAT CGT GAG TTG TAC CAC CGT TTT GAA GTT CTG AGA AAA CCA AGA AAT ATC CGT CTG CTA CCC AGC CGC TCG GTC ACA ACT CTG | |
| | | 310 | 320 |
| | | Glu Ser Ser Gly Pro Gly Trp Lys Leu Leu Met Glu His Leu Asp Gln Gly Arg Glu Ser Leu Glu Ser Asp Val Val Ile Phe Ala | |
| | | GAA AGT ACT GGT CCT GGC TGG AAG TTG CTG ATG GAG CAT CAT CTG GAT CAG GCC AGG GAG AGC CTG GAA AGT GAT GTG ATT TTC GCC | |
| | | 340 | 350 |
| | | Thr Gly Tyr Arg Ser Ala Leu Pro Gln Ile Leu Pro Ser Leu Met Pro Leu Ile Thr Met His Asp Lys Asn Thr Phe Lys Val Arg Asp | |
| | | ACA GGT TAC CGT TCT CGG TTG CCA CAA ATA CTT CCC TCA CTG ATC CGC CTG ATC ACC ATC GAC GAT AAG AAC ACC TTT AAA GTG CCT GAT | |
| | | 370 | 380 |
| | | Asp Phe Thr Leu Glu Trp Ser Gly Pro Lys Glu Asn Asn Ile Phe Val Val Asn Ala Ser Met Gln Thr His Gly Ile Ala Glu Pro Gln | |
| | | GAC TTC ACT CTG GAA TGG AGT GGC CGG AAA GAG AAC AAC ATC TTC GTG GTC AAC GCC ACT ATG CAA ACC CAT GCC ATC CGC GAA CCC CAG | |
| | | 400 | 410 |
| | | Leu Ser Leu Met Ala Trp Arg Ser Ala Arg Ile Leu Asn Arg Val Met Gly Arg Asp Leu Phe Asp Leu Ser Met Pro Pro Ala Leu Ile | |
| | | CTC ACC CTG ATG GCA TGG AGA TCT GCA CGT ATT CTT AAT CGC GTC ATG GGA CGT GAT TTA TTC GAT CTC AGT ATG CGG CCC GCC CTG ATT | |
| | | 426 | 430 |
| | | Gln Trp Arg Ser Gly Thr AM CAG TGG CCC ACC GGC ACC TAG | GGAAAAACGCGAGCCGGAGGCTGCTCTTAACTCGCTACACAGCATCTTGGGCTGATTTTCCGGCGTATGGAGG |

FIG. 2. Nucleotide sequence of *iucD*. Nucleotide sequence of the DNA region of pVLN12 containing the *iucD* gene of the aerobactin operon. The amino acid sequence of the predicted translation product is shown above the nucleotide sequence. The numbers above each line refer to the number of amino acid residues. The segment marked with a line corresponds to the amino-terminal residues of the purified IucD product determined by protein sequencing (see text). Two potential Shine-Dalgarno (S.D.) ribosome-binding sites (47) are indicated. The one assigned to *iucD* is located 9 bp upstream of the initiation codon ATG; the signal at the end of the sequence has been previously ascribed to *iutA*, the next gene in the aerobactin operon (34). Two short regions of dyad symmetry located in the intercistronic sequences surrounding the *iucD* gene are shown by paired arrows. The unique *SphI* restriction site in pVLN12 is also indicated.

fusion product (Table 2) was observed. Incidentally, we observed that cells containing a fusion plasmid named pOV25 excreted increased amounts of hydroxylamine into the culture (as detected with the Csaky test modified by Gillam et al. [21]) and produced a stronger 50-kDa band when analyzed in an SDS-PAGE system. pOV25 consisted of a pVLN12 derivative with a *TnphoA* insertion in *iutA*

oriented opposite to *iucD* transcription (Fig. 4). *E. coli* cells carrying this construction were subsequently used as the source of the approximately 50-kDa protein.

To check whether the IucD'-PhoA and IucD'-LacZ fusion proteins could be entirely located in the periplasm, the corresponding *E. coli* cells were subjected to chloroform shock to release periplasmic proteins (18). No fusion protein

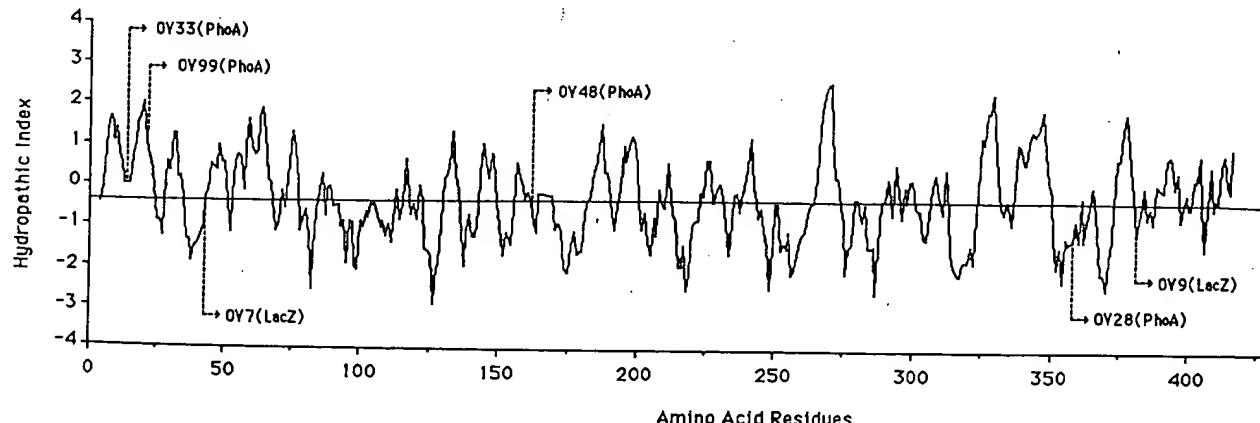


FIG. 3. Hydropathicity profile of IucD protein. The hydropathicity index was determined at a span setting of 7 residues with the algorithm presented by Kyte and Doolittle (35). Hydrophobic regions extend above the middle line. The arrows show the location of the inserts leading to the four *iucD'-phoA* and the two *iucD'-lacZ* gene fusions studied in this work.

was observed in the shock fluid (not shown), ruling out a free periplasmic location.

To ascertain whether domains of the fusion proteins could be accessible from the outside of the cytoplasmic membrane, spheroplasts from every fusion-containing *E. coli* strain (Table 2) were prepared, treated with a low concentration of trypsin, and subsequently analyzed in SDS-PAGE systems. The protein fusion bands from pOV33, pOV99, pOV48, pOV28, and pOV9 faded from spheroplast proteins after trypsin treatment, while that of pOV7 remained insensitive to protease (Fig. 6). Interestingly, in spheroplasts from *E. coli* carrying the intact *iucD* gene, the approximately 50-kDa product was not significantly affected by trypsin (Fig. 6).

DISCUSSION

Results from different groups (16, 24) support the current hypothesis that the biosynthetic route of the siderophore aerobactin in pColV-encoded systems is identical to that proposed by Appanna et al. (1) for *Aerobacter aerogenes* 62-1, the microorganism for which the production of aerobactin was first described. In this scheme, the very first step leading to aerobactin production is the N^6 -hydroxylation of L-lysine, followed by an N^6 -acylation of the corresponding N^6 -hydroxylysine and an eventual condensation of two N^6 -hydroxy- N^6 -acetyl lysine moieties with a citric acid backbone (1, 16, 24).

The presence of an approximately 50-kDa membrane-bound protein as the product of one of the genes of the aerobactin system of pColV-K30 was first shown by Krone et al. (32) and assigned a role in the transport of aerobactin. However, overwhelming evidence from different laboratories later demonstrated that the peptide was instead involved in aerobactin biosynthesis (11, 44), in particular in the step of N^6 -hydroxylation of L-lysine (16, 24) which precedes the eventual synthesis of the aerobactin molecule. This assignment, based on complementation analysis (23) and studies on accumulation of aerobactin precursors by different mutants (16, 24), is consistent with recent in vitro studies made with the unpurified protein (27). In addition, Coy et al. (13) showed that N^6 -hydroxylysine is the substrate for the purified acetylase, the enzyme which mediates the next step in the biosynthetic pathway. Some remaining uncertainties (20) in the biosynthetic pathway of aerobactin synthesis have been addressed elsewhere (3). The gene of the aerobactin

operon encoding this protein was termed *iucD* (16) or, alternatively, *aerA* (23).

The complete sequence of the gene is displayed in Fig. 2 and to our knowledge is the first reported for a biosynthetic gene of a siderophore. The sequence accounts for the production of a predicted 48,968-dalton peptide, a value very close to the approximately 50 kDa observed in mini- and maxicell systems by several laboratories (11, 16, 24, 32, 33).

IucD protein is a moderately hydrophobic polypeptide. Analysis of the 15 amino-terminal residues of the gene product reveals that mature IucD protein is the unprocessed translational product of the *iucD* gene sequence, including the initial ATG codon. The amino-terminal sequence of IucD also resembles that of known signal peptides in that it starts with basic amino acids (lysines at positions 2 and 3) followed by a region rich in hydrophobic residues (Fig. 2). Uncleaved leaderlike sequences are frequently found in inner membrane proteins of *E. coli*, as for instance in the Tet protein from Tn10 or pBR322 (43), the Tsr protein (serine chemoreceptor [8]), the Tar protein (aspartate chemoreceptor [45]), and others.

Analysis of codon usage in *iucD* suggests that it is a rather weakly expressed gene since nonoptimal codons are frequent throughout the sequence, thus possibly reducing the rate of translation. A remarkable feature is the appearance at positions corresponding to amino acids 11, 12, and 13 of a group of three codons (GGG, ACA, and GGG) which are

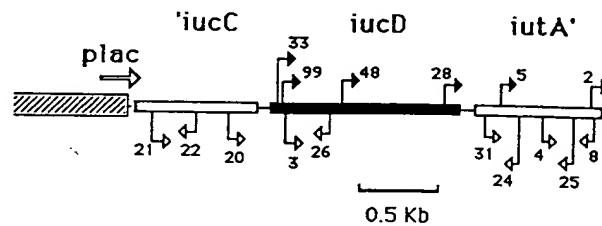


FIG. 4. Positions of TnphoA insertions in plasmid pVLN12. The open arrows indicate the position and orientation of different TnphoA insertions throughout the 3.1-kb insert of pVLN12, the derivative plasmids being identified with the same pOV serial number (see Tables 1 and 2). Solid arrowheads represent insertions that generate in-frame translational sequences. The striped segment of the figure symbolizes the vector portion of constructions.

TABLE 2. Characteristics of '*phoA*' and '*lacZ*' gene fusions in *E. coli* CC118

| Plasmid ^a | Gene fusion | AP activity ^b (U/OD ₆₀₀) | No. of IucD residues in hybrid ^c | Protein size (kDa) | | Hydroxylamine production ^f | β-Galactosidase activity ^g (U/OD ₆₀₀) | |
|----------------------|-----------------------------|--|--|------------------------|--------------------|--|---|-----------------|
| | | | | Predicted ^d | Found ^e | | Permeabilized cells | Intact cells |
| pOV25 | None | ≤1 | 426 | 49 | 47.5 | + | | |
| pOV33 | <i>iucD'</i> -' <i>phoA</i> | 375 | 14 | 48.5 | 50 | - | | |
| pOV99 | <i>iucD'</i> -' <i>phoA</i> | 110 | 21 | 49.5 | 51 | - | | |
| pOV48 | <i>iucD'</i> -' <i>phoA</i> | 12 | 160 | 65 | 61 | - | | |
| pOV28 | <i>iucD'</i> -' <i>phoA</i> | 10 | 357 | 88 | 87 | - | | |
| pOV5 | <i>iutA'</i> -' <i>phoA</i> | 1,700 | N.A. | N.D. | 57 | + | | |
| pOV7 | <i>iucD'</i> -' <i>lacZ</i> | | 42 | 120 | 120 | - | 15,000 | 1,100 |
| pOV9 | <i>iucD'</i> -' <i>lacZ</i> | | 380 | 159 | 152 | - | 1,500 | 580 |

^a Construction and structure of plasmids pOV25, pOV33, pOV99, pOV48, pOV28, pOV5, pOV7, and pOV9 are described in the text and in Table 1. Plasmids were harbored in all cases by *E. coli* CC118.

^b Alkaline phosphatase (AP) activity was assayed by measuring the rate of *p*-nitrophenylphosphate hydrolysis in permeabilized cells (40). *E. coli* CC118 cells carrying the different plasmids were grown in LB liquid culture, washed, and suspended in medium 121 (31) prior to the assay. Values are the averages of three independent experiments.

^c Number of amino acid residues of the IucD product present in the hybrid protein. Every DNA junction fragment was cloned in phage M13 derivatives; its nucleotide sequence was obtained by the dideoxynucleotide chain termination method (46), and from this the amino acid sequence was deduced. N.A., Not applicable (pOV5 contains an *iutA'*-'*phoA* gene fusion and a complete *iucD* gene).

^d Calculated from the position of the *TnphoA* insertion, assuming 47 kDa as the molecular weight of alkaline phosphatase in *TnphoA* (38), and an average molecular weight of 115 for the amino acid residue in the IucD product. In the case of *iucD'*-'*lacZ* fusions, 116 kDa was the mass considered the β-galactosidase contribution (41). N.D., Not determined.

^e Determined for hybrid proteins separated by SDS-PAGE by their rates of migration relative to proteins of known molecular weight.

^f Detection of hydroxylamine-related compound(s) in culture supernatants by the Csaky test as modified by Gillam et al. (21).

^g *E. coli* CC118(pOV7) and *E. coli* CC118(pOV9) cells were washed in Z buffer (41), and their β-galactosidase activity was determined either on cells permeabilized with chloroform and SDS (total activity) or on intact cells to estimate the activity independent of Lac Y permeation (49).

very unusual in the normal codon usage of *E. coli* (22). Clustering of rare codons in signal sequences seems to further decrease the rate of translation (51), which is believed to facilitate early interactions of proteins with the inner membrane (10).

Some features of the mode of association of this protein with the inner membrane were suggested by the study of a number of *iucD'*-'*phoA* and *iucD'*-'*lacZ* gene fusions. The rationale for this approach has been discussed in detail elsewhere (38–40). In summary, alkaline phosphatase is inactive when localized in the cytoplasm (28, 40), and therefore, the activity of a '*phoA*' gene fusion will depend on the translocation of the hybrid protein to the periplasm, or at least the 'PhoA' moiety of the fusion must face the periplasm (38, 39). A similar but less stringent approach can be applied to '*lacZ*' gene fusions carried by *lacY* mutants (defective in lactose permease). In these cells, a hybrid protein localized in the cytoplasmic membrane will afford a remarkable increase in β-galactosidase activity (determined by hydrolysis of *o*-nitrophenyl-β-D-galactoside) after permeabilization of the cells if the 'LacZ' moiety of the protein is cytoplasmic, while a smaller difference will be observed if it faces the periplasm (50).

Four *iucD'*-'*phoA* fusions conferring a PhoA⁺ phenotype were isolated (Table 2). All of them were stable and constituted a major protein component of the cells carrying the corresponding plasmids (Fig. 6). This alone rules out the free cytoplasmic location of the fusions, since alkaline phosphatase is generally quite unstable when exposed to the cytoplasm (38). The hybrid proteins encoded by pOV33 (at the 14th amino acid residue of IucD) and pOV99 (at residue 21) (Fig. 3 and Table 2) afforded a significant level of alkaline phosphatase activity. These proteins did not appear in the periplasmic fluid after chloroform shock, suggesting that the 'PhoA' moiety of the fusion is anchored in the inner membrane and facing the periplasm. Since no information required to act as an export signal or to block export is found in either the alkaline phosphatase or the 17 residues contributed by the IS50_L of *TnphoA* (38), we conclude that the

translocation to the periplasm of 'PhoA' moieties and the final anchoring at the membrane of the two smaller IucD'-PhoA proteins is promoted by the sequence of the first 14 residues from IucD present in both fusions. It is likely that part of these 14 residues forms a thermodynamically stable association with the membrane, probably following a model of membrane-spanning domain closely related to those discussed by Davis et al. (15). These authors have shown that not only hydrophobic α-helices but also strings containing only 11 hydrophobic amino acids can generate membrane-spanning domains. Recent studies have also demonstrated that an anchoring domain can be generated by a short stretch of hydrophobic and neutral residues (19), and even the five to eight consecutive hydrophobic amino acids near the N

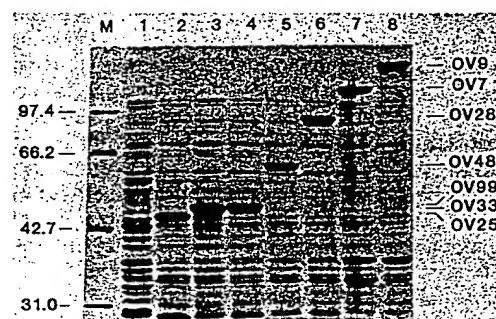


FIG. 5. Analysis of hybrid proteins synthesized in *E. coli* CC118 cells carrying different fusion plasmids. The proteins present in crude extracts of cells were separated by SDS-PAGE (8% acrylamide) and stained with Coomassie blue. Lanes: M, molecular weight markers (in thousands); 1, control *E. coli* CC118, no plasmid; 2, control *E. coli* CC118(pOV25) (pOV25 carries a *TnphoA* insertion in *iutA* which leaves intact *iucD*; see Fig. 4); 3, *E. coli* CC118(pOV33); 4, *E. coli* CC118(pOV99); 5, *E. coli* CC118(pOV48); 6, *E. coli* CC118(pOV28); 7, *E. coli* CC118(pOV7); 8, *E. coli* CC118(pOV9). The protein products IucD, the four IucD'-PhoA fusions, and the two IucD'-LacZ fusions can be identified as the major bands in lanes 2, 3 to 6, and 7 to 8, respectively.

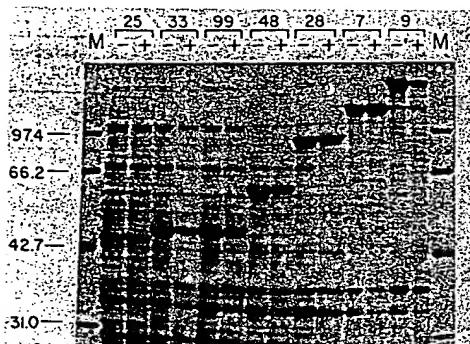


FIG. 6. Accessibility of IucD'-PhoA and IucD'-LacZ protein fusions to trypsin in spheroplasts. A Coomassie-blue stained SDS-PAGE system (8% acrylamide) loaded with spheroplasts from cells harboring gene fusion plasmids is shown. Numbers on top refer to the number of the OV fusion plasmid carried in each case by *E. coli* CC118 cells. Treatment of the spheroplasts with trypsin is indicated above each lane. Cells with the construction pOV25 were introduced as a control: pOV25 carries a *TnphoA* insertion in *iutA* which leaves intact *iucD* (see Fig. 5). Lanes M contained molecular weight standards (in thousands).

terminus of a 'LacZ' protein fusion can serve to anchor a functional β -galactosidase to the inner membrane of *E. coli* (12).

Since the leading region of 14 and 21 amino acids in the fusions OV33 and OV99, respectively, appears to be enough to promote the export of their PhoA moiety, it is likely that the leading peptide is also able to promote interactions of the IucD product itself with the membrane. The leading region of at least 14 amino acids might define a first domain of attachment of this protein to the cytoplasmic membrane.

The levels of alkaline phosphatase afforded by the PhoA⁺ fusions encoded by pOV48 (*TnphoA* insertion at residue 160 of IucD) and pOV28 (at residue 357) were much lower than the levels detected in the presence of pOV33 and pOV99 (Table 2), although the corresponding proteins were equally stable and synthesized in similar quantities (Fig. 5).

Two *iucD*'-'lacZ' gene fusions were prepared in vitro by ligating the 'lacZ' gene to residues 42 and 380 of IucD sequence in plasmid pVNL12, generating, respectively, plasmids pOV7 and pOV9. Both of them yielded rather high β -galactosidase activities in *E. coli* CC118 cells, which lack lactose permease. It is remarkable that permeabilized cells with fusion plasmid pOV9 increased only 2.5 times their β -galactosidase activity levels compared with intact cells, while the corresponding increase detected in cells with pOV7 was over 12-fold. In *lacY* cells the activity of cytoplasmic free β -galactosidase increased usually over 10 times after permeabilization (not shown). β -Galactosidase values suggested that the 'LacZ' moiety in the pOV9 protein fusion is facing the periplasm, while that of pOV7 is facing the cytoplasm. Both hybrid proteins were stable and synthesized in similar amounts, but the total β -galactosidase activity levels were some 10-fold higher with pOV7 than with pOV9.

A final set of assays was carried out to check whether domains of the IucD'-PhoA and IucD'-LacZ fusion proteins could be facing the periplasm. For this purpose, spheroplasts from cells carrying the fusions were prepared and treated with trypsin, and their protein profiles were compared with those of untreated spheroplasts (Fig. 6). Although spheroplasts from cells carrying pOV25 with the functional *iucD* gene did not reveal a significant degradation of the approximately 50-kDa IucD protein, all four IucD'-

PhoA fusions appeared to be sensitive to trypsin, since analysis in an SDS-PAGE system showed that the corresponding bands disappeared at high trypsin concentrations (not shown) or at least faded after protease treatment (low trypsin concentration, Fig. 6). With respect to the IucD'-LacZ fusions, Fig. 6 also shows that the fusion from pOV9 was heavily degraded, while that of pOV7 remained virtually intact. These last two fusions (OV7 and OV9) provided reasonable controls for the performance of the procedure, because cytoplasmic PhoA fusions are unstable (38) and would therefore be unreliable as controls in this type of experiment.

It is known that fusions of some exported proteins to 'LacZ' are lethal to *E. coli* cells when produced in large amounts, a phenomenon explained as jamming of the export machinery and concomitant accumulation of precursor forms of other exported proteins (5, 29, 40, 50). Although the signal sequences of the corresponding proteins (i.e., alkaline phosphatase, maltose-binding protein, etc.) are capable of directing β -galactosidase to the membrane, the export is not completed and the hybrid proteins become membrane bound. Since the 'LacZ' moiety was never found translocated into the periplasm, it was considered that β -galactosidase is not competent to cross through the lipid bilayer (40). In our case, the small difference found in β -galactosidase activity between permeabilized and intact cells containing plasmid pOV9, together with the apparent accessibility of the same pOV9-encoded hybrid protein to trypsin digestion in spheroplasts, indicate that the 'LacZ' moiety has been mobilized into the periplasm, and therefore that β -galactosidase can indeed be translocated. This also shows that membrane-bound proteins fused to 'LacZ' can be synthesized in large amounts, apparently without deleterious consequences. Probably the IucD product is localized in or at the inner membrane independently of the export machinery, and this fact circumvents the problem arising from blockage of the export pathway detected in the study of some other hybrid proteins (5, 29, 40).

The previous results support the association of the *iucD* gene product with the inner membrane of *E. coli* cells, with the bulk of the protein facing the inner side and with at least two attachment sites which extend into the lipid bilayer. One of them would be at the leading sequence of the protein and is defined by the 'phoA' fusions of pOV33 and pOV99, while the other occurs towards its terminal portion and is defined by the 'lacZ' fusion of pOV9. This last domain may also account for the 'phoA' fusion of pOV28. Although the peptide sequences which probably protrude into the membrane afford translocation of the 'PhoA' and 'LacZ' moieties of those fusions into the periplasm, there is no evidence that the IucD product itself has any domain exposed to the periplasm. An additional region of attachment to the membrane could occur in the region close to residue 160, accounting for the PhoA fusion of pOV48, since cells with that plasmid show detectable alkaline phosphatase activity and the corresponding fusion protein is sensitive to trypsin in spheroplasts. The low activity of the IucD'-PhoA proteins encoded by pOV48 and pOV28 may result from an unusual type of association with the membrane that could affect some of the steric requirements for activation of alkaline phosphatase (39).

The location of the IucD product makes biological sense. As this enzyme is involved in iron metabolism and probably requires molecular oxygen for its activity (3), its membrane location would contribute to maintenance of a reducing intracellular milieu.

Important features of the gene product of *iucD* remain uncertain, mostly those regarding its enzymology. We think that the information on the gene sequence and the characteristics of the protein described here will contribute to the elucidation of a rational scheme for its purification and, ultimately, to the discovery of inhibitors of its activity.

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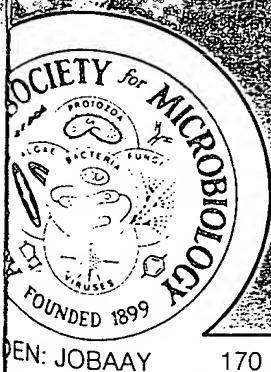
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